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Airframes and Engines Division
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ABSTRACT

DSTO has been continuously enhancing its capability to provide through-life support to the ADF in aircraft engine life extension and engine component life management. One of the major requirements is an enhancement in computational 3D crack growth modelling and analysis. This report presents the critical issues involved in 3D crack growth and evaluates the results of a 3D crack growth capability in the ZENCRACK software with an emphasis on its validity and applicability to our major requirements. The primary issues to be dealt with in practice for 3D crack modelling are outlined together with the limitations of existing software. The methodology and techniques implemented in ZENCRACK are described and discussed. Four practical applications of ZENCRACK and individual evaluations for particular problems are presented and discussed in detail. The various limitations and uncertainties encountered in the practical applications are identified. In particular, it is found that ZENCRACK is a useful tool for the calculation of stress intensity factors but is limited in terms of its accuracy for predicting crack growth rate. Conclusions and recommendations are made for more accurate 3D crack growth modelling.

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Executive Summary

DSTO has been continuously enhancing its capability to provide through-life support to the ADF for aircraft engine life extension and engine component life management. One of the major requirements is an enhanced capability in 3D crack growth modelling and analysis. This aspect has a significant impact on the thoroughness and timeliness of advice on life assessment and management of critical engine components, especially for the F-111 aircraft that has been planned to continue in service up to the year 2020.

This report summarises the evaluation results of the 3D crack growth in ZENCRACK software capability with an emphasis on its validity and applicability to our major requirements in the area of 3D crack growth prediction. Among various difficulties and uncertainties involved in 3D crack growth modelling, two distinct issues are identified i) accurate calculation of the stress intensity factor along a 3D crack front embedded in a component with complex geometry; ii) effective determination of the crack growth in 3D space. Most existing crack growth models and codes are limited to 2D crack problems or 3D planar crack problems because of the lack of closed form solutions for stress intensity factors. This limitation has been successfully overcome by combining advanced Finite Element techniques with basic principles in fracture mechanics. These techniques implemented in ZENCRACK are described and discussed in this report. Four practical applications of ZENCRACK and individual evaluations for particular problems are presented and discussed in detail. Both mechanical and thermal loads can be included in the calculation of stress intensity factor and crack growth. The sub-modelling technique can be used together with ZENCRACK. It is found that ZENCRACK is most useful for inserting cracks with complicated shapes into existing 3D FE meshes. The automated crack block mesh significantly reduces meshing time and modelling complexity so that stress intensity factors can be readily calculated for almost any crack shape inserted in a component with a complicated 3-D geometry.

ZENCRACK is assessed as being a useful tool for the calculation of stress intensity factors for cracks inserted into 3-D components under arbitrary loadings. However, the crack growth analysis in ZENCRACK is based on the basic principles of linear elastic fracture mechanics and therefore is limited in its application only to crack growth analysis in the linear elastic domain. For more accurate prediction of crack growth, advanced models need to be implemented and utilised together with 3D numerical analysis techniques.

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Jianfu Hou completed a B. Eng. (1st class Hons) in 1985 and a M.E. in 1988 at Jilin University of Technology. In 1995 he was awarded the degree of Doctor of Philosophy in Engineering from Royal Melbourne Institute of Technology (RMIT). From 1990 to 1991, he was a Visiting Research Fellow working on rotor dynamics in the University of Melbourne. In 1992, He joined the Vehicle Safety Research Group at RMIT and worked on injury reduction of car occupants through the design optimisation of airbag and seatbelt restraint systems jointly with GMHA. From 1995 to 1998, he was employed by Worley FEA as a Senior FE Analyst - Dynamics and Fatigue Specialist. In March 1998, he joined AED as a research scientist and since then he has been working on engine component life management at AMRL. His research interests include computational mechanics and dynamics of engine rotor systems, fatigue life assessment, design optimisation and impact simulations.

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Contents

1. Introduction

DSTO has been continuously enhancing its capability to provide through-life support to the ADF for platform life extension and life management [1, 2]. One of the pressing requirements, particularly for aero engine components, is to develop a capability in 3D crack growth modelling and analysis. Estimates of residual life based on crack growth can have a significant impact on the quality of the advice to RAAF in the life management of critical engine components, especially for the F-111 aircraft that has been planned to continue in service up to the year 2020. There are various issues and difficulties involved in 3D crack growth analyses. In general, the difficulties associated with 3D crack growth analysis can be grouped into two categories: a) accurate calculation of stress intensity factors along a 3D crack front embedded in a component with complex geometry; b) effective determination of the crack growth rate in 3D space.

The stress intensity factor can be readily calculated for most 2D cases based upon the information in various references and handbooks [3-4]. However, this can be very difficult for 3D problems because of the lack of closed form solutions. For complicated configurations it is often impossible to derive an analytical solution of the stress intensity factor. Alternatively, the Finite Element (FE) method may be used to determine stress intensity factors numerically. However, in order to simulate the stress and strain singularity at a crack tip, special crack tip elements have to be generated. The modelling process can be very time consuming, especially in 3D cases. Therefore it is desirable to automate the generation of crack elements with a good quality mesh so that more accurate numerical solutions can be obtained.

There are a number of crack growth models and analysis codes [5-9] available, but most of them are limited to 2D or 3D planar crack growth analysis for a crack embedded in a simple geometry. The crack propagation direction and the amount of growth are two essential aspects to be determined in a general 3D crack growth analysis. In the 2D case the crack growth direction is predescribed and updated by the distribution of the stress intensity factor along a crack front, and the growth progresses with crack length increments. In 3D cases the crack growth direction has to be interactivity determined along the 3D crack front. In practice, the loading conditions are quite complex; in the case of gas turbine engines involving centrifugal loads, thermal loads and assembly loads. In some 3D cases [10-11] a particular feature can be idealised to a known representative model such that both the component geometry and the loading conditions can be simplified. However, in some cases this idealisation may be impossible due to the fact that there is not a known geometry which can be used for simplifications. Therefore 3D crack growth prediction is a generic problem for components with irregular geometry under complex loading loading conditions and remains as a challenge for most crack growth analysis codes.

For successful predictions of 3D crack growth, more sophisticated approaches have to be adopted by combining the Finite Element (FE) method and established crack growth laws in fracture mechanics. ZENCRACK software by Zentec Inc [12] has been

developed specifically for general 3D crack growth analysis. The basic concept is that the FE method can be used to determine the accurate stress intensity factor values for a generalised 3D crack and the principles characterising the crack growth in 3D cases then can be utilised to predict crack growth behaviour.

This report summarises the evaluation results of the ZENCRACK software capabilities with an emphasis on its validity and applicability to major DSTO requirements. Section 2 outlines the primary issues to be dealt with in practice for 3D crack modelling and the limitations of existing software. Section 3 describes the methodology and techniques implemented in ZENCRACK. Section 4 details four practical applications of ZENCRACK and individual evaluations for particular problems and also provides the detailed discussion on the various limitations and uncertainties encountered in the practical applications. Section 5 summarises the conclusions and recommendations from the evaluation on the issues involved in 3D crack growth prediction.

2. Issues in 3D Crack Growth Prediction

2.1 Issues Considered

There are numerous factors and uncertainties involved in the 3D crack growth analyses of components. Two distinct issues have to be dealt with:

a) Accurate calculation of stress intensity factors along the 3D crack front.
b) Effective determination of the crack growth in 3D space.

Difficulties in determining the stress intensity factor may arise for 3D situations often because of lack of closed form solutions. The complexities arising from both 3D geometry and loading conditions are also of major concern. A component with a relatively simple geometry may be idealised to a known simplified model and then the stress intensities can be calculated, provided the cracks are planar in 3D space. However, this idealisation is not possible for components with a combination of complex geometry and loading condition. The typical examples are engine discs and spacers with 3D cracks at local features such as the snap radius [13] and flange cutouts.

Most crack growth models and analysis codes [5-9] can be used for only 2D crack growth or 3D planar crack growth with a simplified geometry, often because of the lack of a formulation for the stress intensity factor for 3-D cases. The crack propagation direction and the amount of the growth are two essential parameters to be determined in general crack growth analysis. In both 2D and 3D cases the crack growth direction is determined by the direction of the maximum energy release rate and the growth progresses with a specified crack growth increment. Therefore the methodology for crack growth analysis is essentially identical for the 2D and 3D cases, but 3D crack growth requires more analysis due to the complexities involved.

2.2 Limitations of Existing Packages

Fastran [5] and Afgrow [6] are two other popular crack growth packages. Fastran in particular has been reviewed and validated for 2D cases. For 3D crack growth analysis, there are various limitations in these codes that can be identified.

1. They deal only with simplified crack geometries representing 3-D geometry behaviour under simple loading conditions;
2. The semi-empirical constraint coefficient/factors are unknown for many 3D crack configurations;
3. Thermal load and temperature effects can not be easily included in crack growth analysis;
4. There are difficulties involved in estimating the loading conditions for the idealised geometry from 3D components.

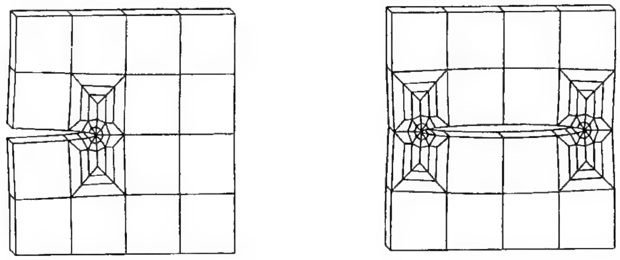
These limitations have restricted the applicability of these codes for 3D crack growth prediction.

3. Methodology Implemented in ZENCRACK

3.1 3D FE Crack Block Modelling

To simulate the stress and strain singularity at a crack tip, elements with middle side nodes have to be shifted to quarter points towards the crack tip [29]. In finite element modelling this has to be performed by translating the middle side nodes and can be very tedious and time consuming, especially for 3D cases. Also 3D mesh transitions of crack elements can be very difficult for manual modelling since there is a very large change in typical element size between the crack tip region and the rest of the structure. The mesh quality of crack elements directly affects the precision of the calculated stress intensity factor values and therefore it is desirable to automate the generation of crack elements from a FE model.

The automatic generation of 3D crack elements that has been implemented in the computer code ZENCRACK [12] has a direct interface with FE code ABAQUS [14]. ZENCRACK can be easily used for the efficient generation of 3D crack elements. The basic principle used in ZENCRACK is that a crack block, defined by a normal 20 noded element, can be replaced by a group of crack elements to form a desired crack front. The crack front can be either semi-circular/semi-elliptical or linear within a crack block. Therefore, either a 3D surface crack or a through crack can be inserted by combining different crack blocks. Figure 1 demonstrates typical 3D cracks meshed using ZENCRACK.



a.) surface crack *b.) center crack*

Figure 1. Crack tip element generation using ZENCRACK crack-blocks and split pairs

3.2 Stress Intensity Factor Determination

Based upon a cracked FE model the stress intensity factor can be determined at each node along the crack front using the J-integral method in ABAQUS. It can be related to the stress intensity factor directly for the case of the linear material response. The J-integral is defined as the energy release rate associated with crack advance. Assuming a virtual crack advance $\lambda(s)$ in the plane of a 3D crack growth, the J-integral can be expressed as [12,14]:

$$G = \int_A \lambda(s) \boldsymbol{n} \cdot \boldsymbol{H} \cdot \boldsymbol{q} da \tag{1}$$

Where,
G is the energy release rate,
da is a surface element along a vanishing small tubular surface enclosing the crack tip,
$\boldsymbol{n}$ is the outward normal vector to da,
$\boldsymbol{q}$ is the local direction vector of virtual crack advance.

$\boldsymbol{H}$ is a matrix, defined as:

$$\boldsymbol{H} = (W\boldsymbol{I} - \boldsymbol{\sigma} \cdot \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}}) \tag{2}$$

Where
W is the elastic strain energy for elastic material behaviour,
$\boldsymbol{I}$ is a unit matrix,
σ is the stress matrix,
$\partial \boldsymbol{u}/\partial \boldsymbol{x}$ is the strain matrix.

The J-integral should be independent of the domain selected, but the values for different rings may vary slightly for a given crack front because of numerical differences in the FE solution. Therefore the FE mesh has to be controlled in order to minimise the variation in the calculated J-integral values. It is usually recommended by ABAQUS that at least two rings/contours should be used for the evaluation of the J-integral value [14]. In this study the element sizes were 10% of the crack length.

In the case of linear-elastic material behaviour, the energy release rate G can be related to the stress intensity factor as follow [4,12]:

$$G = \frac{[1-(\alpha\upsilon)^2]K^2}{E} \tag{3}$$

Where

E is the Young's Modules of material,

υ is the Poisson's ratio of material,

K is the stress intensity factor,

α is a constant, $\alpha = 1$ for plane strain condition and $\alpha = 0$ for plain stress.

Hence, the stress intensity factor can be determined from the J-integral values along the crack front by rearranging equation (3).

3.3 Crack Growth: Virtual Crack Extension Method

Determining the direction of 3D fatigue crack growth can be very difficult for a crack with 3-D arbitrary shape under a generalised loading condition. This is due to the fact that the direction of crack growth is governed by a combination of all three loading modes K_I, K_{II} and K_{III} (I, II, II) corresponding to stress intensities. No satisfactory method has yet been developed to predict 3D crack growth if an effective stress intensity calculated from the strain energy release rate is used.

In ZENCRACK, the crack growth direction is determined to be the direction of the maximum energy release rate describing the formation of new crack surfaces under any state of stress [15-19]. The method is based on the virtual crack extension method proposed by Hellen [15] and Billardo [16]. The virtual extension method can be described as follows.

For a given virtual crack extension *da*, the change in strain energy in a particular direction *dG* can be calculated from energy release rate G determined from FE:

$$G = -\frac{dG}{da} \tag{4}$$

The distribution of the strain energy release rate at a node (in a plane normal to the crack front) then may be calculated using Equation (4) and the direction with the maximum strain energy release rate is identified as the crack growth direction. By

assuming the mode I loading condition, the crack growth law then can be expressed directly by the strain energy release rate in the form of Paris equation as:

$$da/dn = C'(G_{\max}^{1/2} - G_{\min}^{1/2})^m \tag{5}$$

Where,

da/dn is the crack growth rate,
C' is a material constant,
$G_{\max}$ is the maximum strain energy release rate during a load cycle,
$G_{\min}$ is the minimum strain energy release rate during a load cycle,
m is a material constant.

As shown in Equation (5), the crack growth rate has been directly related to the energy release rate to take into account any state of stress for a crack growth analysis under a generalised loading condition. Therefore the experimental crack growth data, ie the stress intensity factor vs crack growth rate, has to be converted to a strain energy release rate (refer to Equation 3). In ZENCRACK, the minimum energy release rate $G_{\min}$ and the maximum energy release rate $G_{\max}$ are assumed to be in the identical direction of $G_{\max}$ and this may have an effect on the accuracy of crack growth prediction under non-proportional loading conditions.

3.4 Crack Growth Procedure in ZENCRACK

The procedure of the iterative 3D fatigue crack growth prediction is shown schematically in Figure 2.

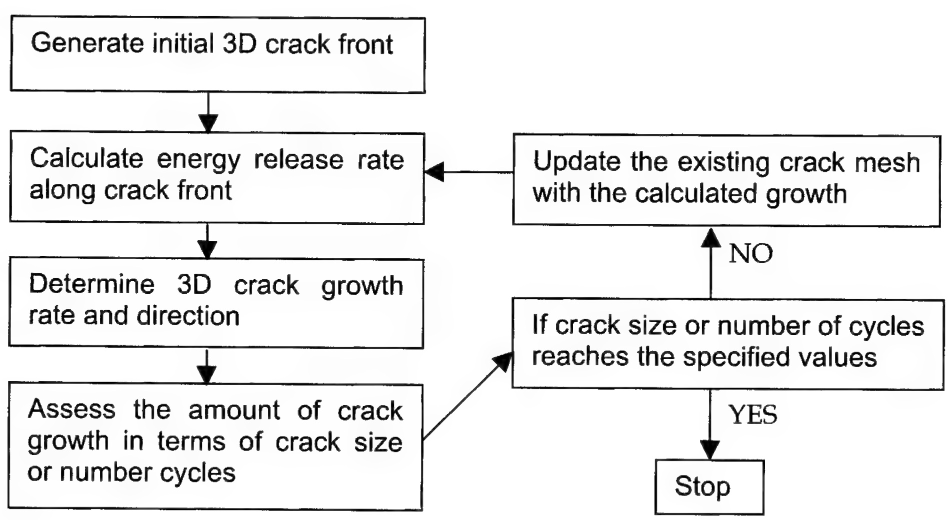


Figure 2. ZENCRACK 3D crack growth procedure

The crack growth starts with the generation of an initial crack and the stress intensity factors are calculated. The crack growth direction and the amount of growth are then determined by the virtual extension method and the crack front is updated. This process is repeated till the crack size or number of cycles reaches the limit.

4. 3D Crack Growth Prediction Using ZENCRACK

4.1 Modelling Cracks in a Marine Propeller

4.1.1 Background

The design of marine propellers has traditionally been based on a S-N approach, however a fracture mechanics approach is more appropriate for propellers containing significant crack-like defects. The finite element program ABAQUS was used together with the utility program ZENCRACK to calculate the stress intensity factor along the crack front for cracks with various aspect ratios in a propeller blade made from a linear-elastic material. The propeller blade was placed under bending stresses by a point load.

4.1.2 Problem Definition and Solution

To correctly predict the stresses through the thickness of the propeller under bending, at least two elements are required through the cross section, which is also stipulated in the ZENCRACK user's manual. For the propeller model, four elements were used through the thickness of the propeller so the stresses were accurately calculated. Small semi-elliptical cracks were modelled in the 3D propeller model using ZENCRACK, utilising four crack blocks to describe each quarter of a particular crack, which correctly models the elliptical shape. Figure 3 shows the cross section of the local region with a crack. When the crack length and crack depth are less than the element length ZENCRACK is successful at modelling semi-elliptical cracks.

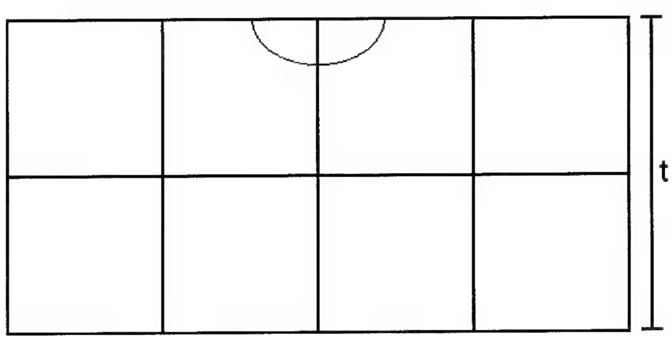


Figure 3 A finite element mesh with small elliptical crack in a propeller of thickness, t successfully modelled using ZENCRACK

A long semi-elliptical crack could be modelled in ZENCRACK but crack blocks with a straight edge and quarter elliptical edges are required. (Figure 4) The black line in figure 4 describes the geometry of the semi-elliptical crack to be modelled. The bold black line describes the approximation of the crack shape using the ZENCRACK crack blocks, which do not accurately describe the shape along the crack front and results in the poor prediction of the stress intensity factor along the crack front.

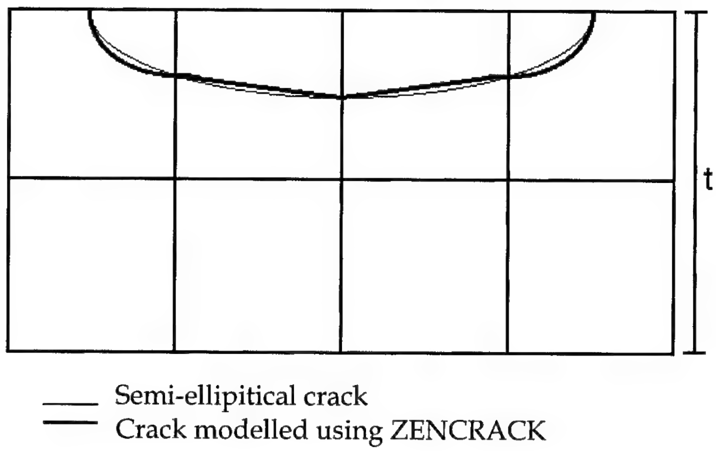


Figure 4 *A finite element mesh with long elliptical crack in a propeller of thickness, t not successfully modelled using ZENCRACK.*

Deep cracks greater than half the propeller thickness were proposed to be modelled using ZENCRACK but this was not found to be possible. For a propeller in bending at least two elements are required through the thickness so the stresses are correctly described. As a result, crack blocks with a straight edge and quarter elliptical crack blocks are required. When using this combination of crack blocks the crack front is not properly modelled, resulting the poor prediction of the stress intensity factor (figure 5).

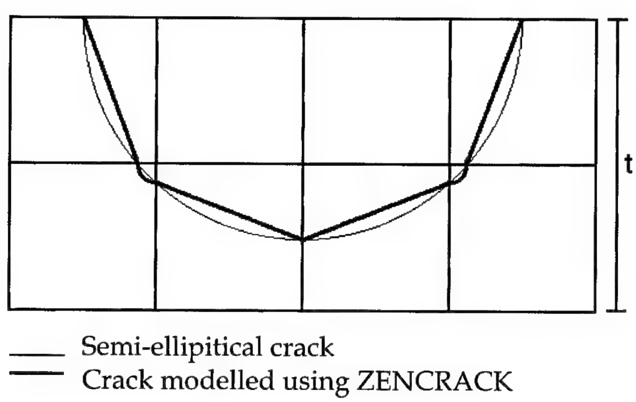


Figure 5 *A finite element mesh with deep elliptical crack in a propeller of thickness, t not successfully modelled using ZENCRACK*

4.1.3 Conclusions

The program, ZENCRACK was found to be successful in modelling small semi-elliptical cracks where the crack length and depth were less than the element length for a bending problem. However additional care had to be taken when using ZENCRACK to model long cracks or deep cracks for a bending problem. This is because the crack front could not be precisely described using a combination of crack blocks. In these cases, remeshing of models is necessary.

4.2 3D Crack Growth Analysis for a Compact Tension Specimen

4.2.1 Problem Definition

The objective of this particular study was to verify the capability of ZENCRACK to predict crack growth behaviour of a specimen experiencing cyclic loading under plane stress, plane strain and mixed mode conditions. The intention was to validate the software by comparing the results generated by ZENCRACK to a standard Compact Tension (CT) specimen for which data and experimental results were available. After validation the intention was to extend the investigation to evaluate ZENCRACK's capability to model the phenomenon known as stable tearing or crack jumping.

The CT specimen had dimensions as detailed below in Figure 6.

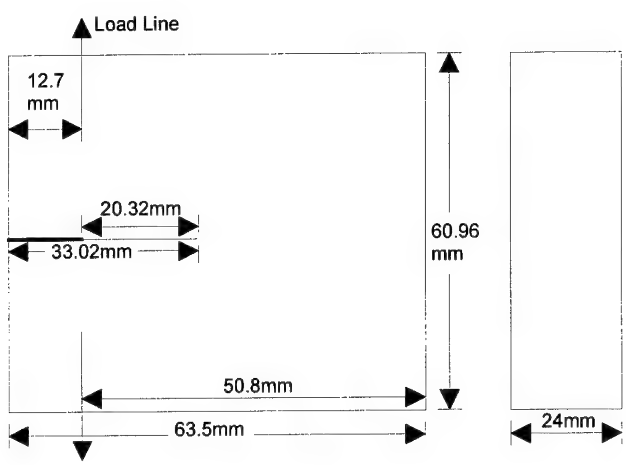


Figure 6. Compact tension specimen

The base finite element (FE) mesh developed to model the CT specimen is shown in Figure 7. The resulting mesh after crack blocks were inserted is shown below in Figure 8.

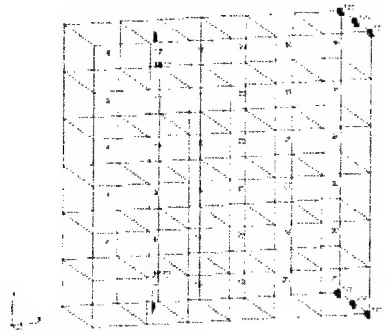


Figure 7. Base finite element model

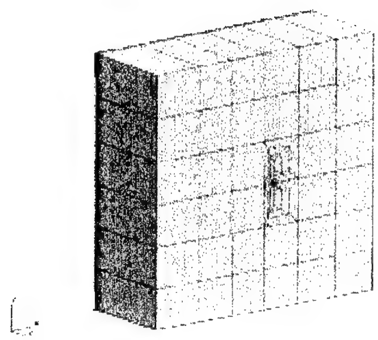


Figure 8. FE model with elements 21 & 22 replaced by crack blocks

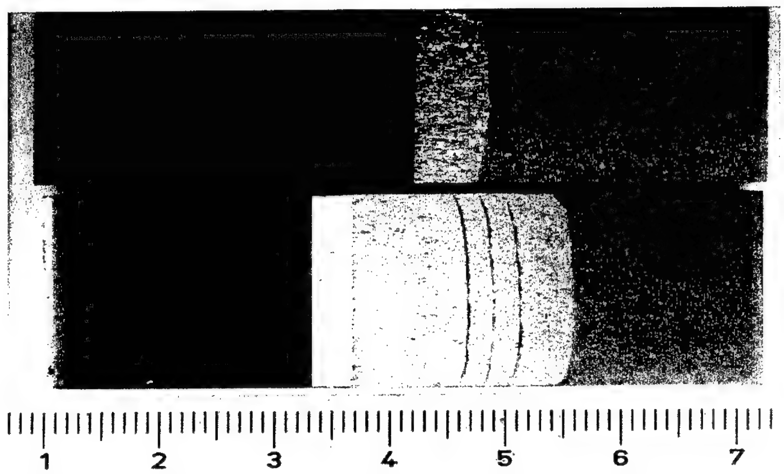
Material was aluminium alloy 7050-T7351. Variations on the model were made to investigate plane stress behaviour (with reduced thickness) and to use the restart options with a reduced mesh density.

4.2.2 Analysis Procedure and Method

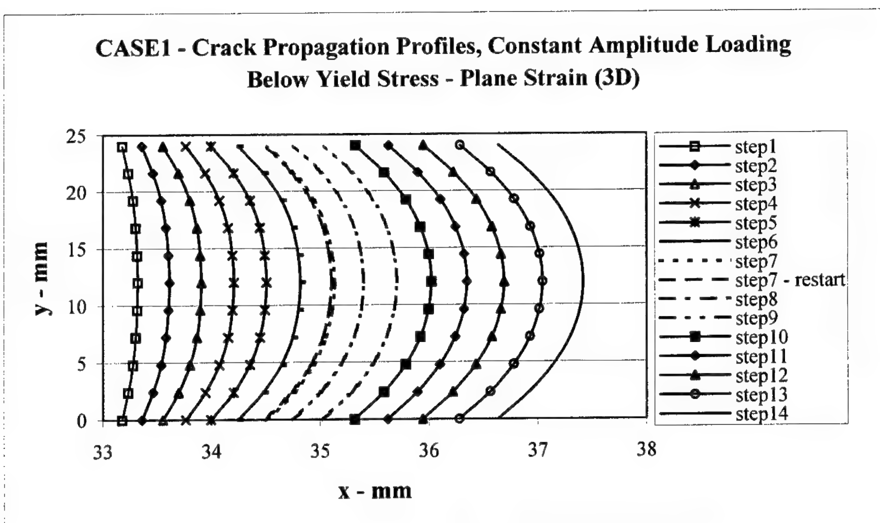
A number of the facilities available in ZENCRACK were tested in this investigation including its ability to implement crack growth based on the linear region of the Paris equation, the restart option, which permits extended crack growth, and the use of the load spectrum input. The main focus was on the software's capability to predict fatigue crack growth behaviour and the associated crack front profiles observed under physical test conditions. ZENCRACK was used in the context of a comparative investigation and not as a tool to solve a given problem. ZENCRACK was used in a standard fashion by implementing a known crack growth law from experimental data, applying a representative fatigue load spectrum and observing the crack front profiles, stress intensity factors and crack growth rates. The finite element solver used was ABAQUS. Each analysis step was performed by setting a desired number of load spectra (in this case, one per step).

4.2.3 Results and Discussion

Crack front profiles under plane strain were successfully modelled using ZENCRACK and ABAQUS with a general agreement between observed and experimental behaviour (refer to Figure 9 for crack profiles). This suggests that ZENCRACK would be useful for predicting crack growth behaviour under these conditions.



a.) Crack profiles from experiment



b.) Crack profile from ZENCRACK prediction

Figure 9. Crack Front Profiles Under Non-Controlled Plan Strain

Pure plane strain conditions, free of 3D surface effects, were achieved through suitable control of boundary conditions. This enabled ZENCRACK to produce straight crack front profiles (see Figure 10). Crack front profiles under plane stress and mixed plane

stress and plane strain were successfully modelled using ZENCRACK and ABAQUS. The correlation between the models and experimental data was good, but the large distortions often observed in crack front profile under plane stress and mixed loading were not reproduced by ZENCRACK. Reducing specimen width did not help capture this effect. ZENCRACK therefore appears to be useful for modelling such conditions for indicative purposes only.

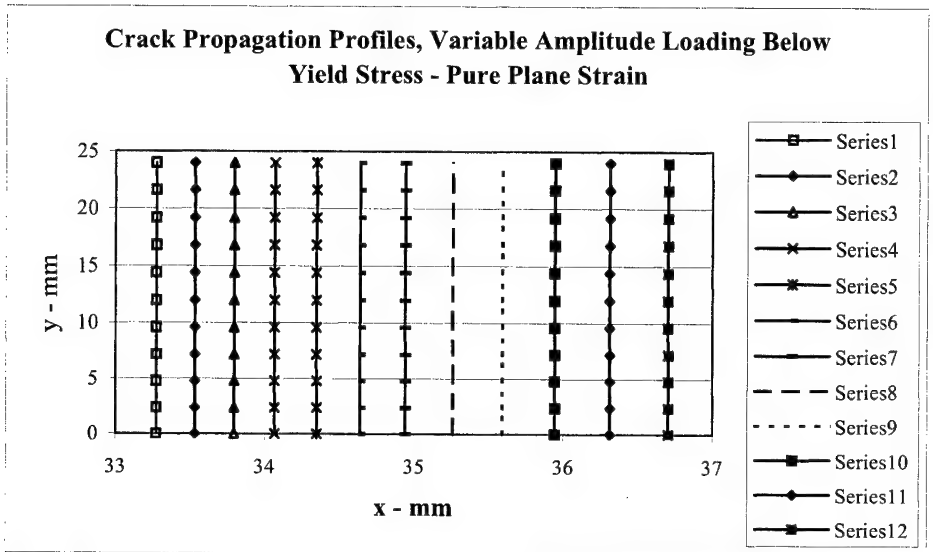


Figure 10. Crack Front Profiles Under Controlled Plane Strain

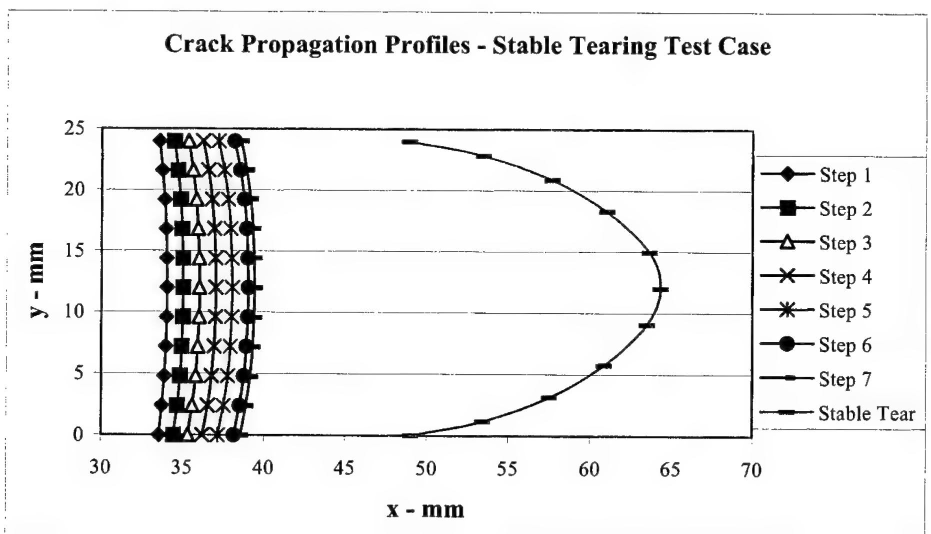


Figure 11. Modelling Stable Tearing

The phenomenon of stable tearing was also modelled using ZENCRACK. However, careful control over the analysis was required. It was possible to emulate the behaviour of materials undergoing crack jumping due to an excessive single load. However, the crack growth recorded for the test was outside the bounds of the Paris equation and therefore the results were unreliable.

There are several significant limitations that ZENCRACK places on any analysis. Fatigue crack growth for a variable load spectrum is not accurately modelled due to the implementation of the characteristic K method that averages the fatigue load spectrum. It is also a simplified crack growth analysis technique. Crack growth outside the region governed by the Paris equation is only extrapolated from the given data. Large growth is limited by both the Paris equation and the ability for ABAQUS to handle the distorted mesh.

ZENCRACK is useful for developing cracked finite element models of complex, 3D shapes. The concept of the crack block library coupled with the user's ability to control mesh density and distribution within the crack block makes this function of the program applicable to almost any cracked structure. Linking ZENCRACK to ABAQUS also permits the accurate determination of stresses and displacements arising due to the presence of a crack when a single analysis, without crack growth, is employed. This is the most advantageous aspect of the software.

4.2.4 Conclusions

ZENCRACK is useful for qualitatively investigating crack front behaviour under cyclic fatigue conditions for plane strain. To accurately model such conditions careful control of the restraint of the finite element model is required to avoid 3D edge effects. ZENCRACK does not accurately represent plane stress conditions in that crack front profiles on the CT specimen do not appear as they do in physical test specimens– the general behaviour can be modelled but the accuracy of the results is dubious.

The phenomenon of stable tearing could be reproduced with reference to a CT specimen, but only with careful control over the analysis. Therefore representative behaviour only could be modelled. ZENCRACK could not be used to predict whether stable tearing would occur under cyclic loading with intermittent overload spikes.

The software is limited in its capability for accurate prediction of fatigue crack growth. This arises from the fact that growth rate can be outside the region covered by the Paris equation. The limitation on crack growth accuracy due to the ratio of crack block side length to crack length (minimum 15% and maximum 70%) has a significant influence over FE mesh size. To grow cracks reliably beyond the 70% limit a restart is required which requires complete re-meshing of the crack site. This can be time consuming in complicated models.

The greatest advantage of the software is its ability to place a crack of almost any geometry into any 3D structure with relative ease. Submitting this modified model to

the FE solver and calculating the resulting stress and displacement distributions significantly speeds up such a process. However, calculating the growth of such a crack is limited by both the accuracy of the analysis and the need to conduct a restart analysis to obtain significant crack growth.

4.3 3D Crack Growth Analysis for Black Hawk Tail Rotor Output Shaft

4.3.1 Background

Several years ago, a United States (US) Army Black Hawk suffered a non-fatal crash when its Tail Rotor Output Shaft (TROS) failed. A similar failure of the TROS in a Chinese Black Hawk resulted in a fatal crash. Manufacturing defects were responsible for the failures and the ADF, supported by AED, took appropriate action at the time to ensure the integrity of shafts in Australian Black Hawks and Seahawks. However, the failures of the shafts raised questions about the capability of helicopter components to tolerate manufacturing flaws. The primary objective of the work presented in this report was to obtain information relating to crack growth rates that a TROS experiences during flight.

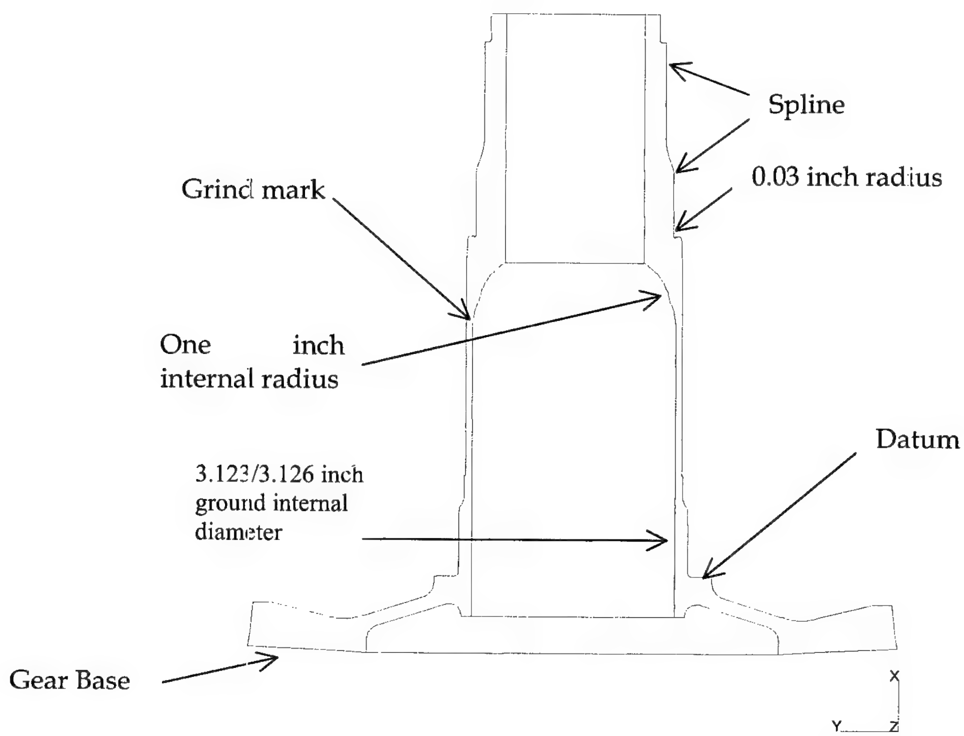


Figure 12. Cross-section of the TROS.

Figure 12 presents a cross section of the TROS showing various details. Initially a three-dimensional FE model of the TROS was created to detect any stress concentrations at

the initiation site of the crack in the US Army Black Hawk TROS. A stress concentration was found that varied by up to 15% due to various geometrical differences between specimens. The decision to perform a crack growth analysis on the TROS was then made to gain a better understanding of the failure of the US Army Black Hawk TROS. Figure 13 shows the location and type of crack blocks used in the ABAQUS mesh of the TROS. Spring elements were used to represent the bearing supports.

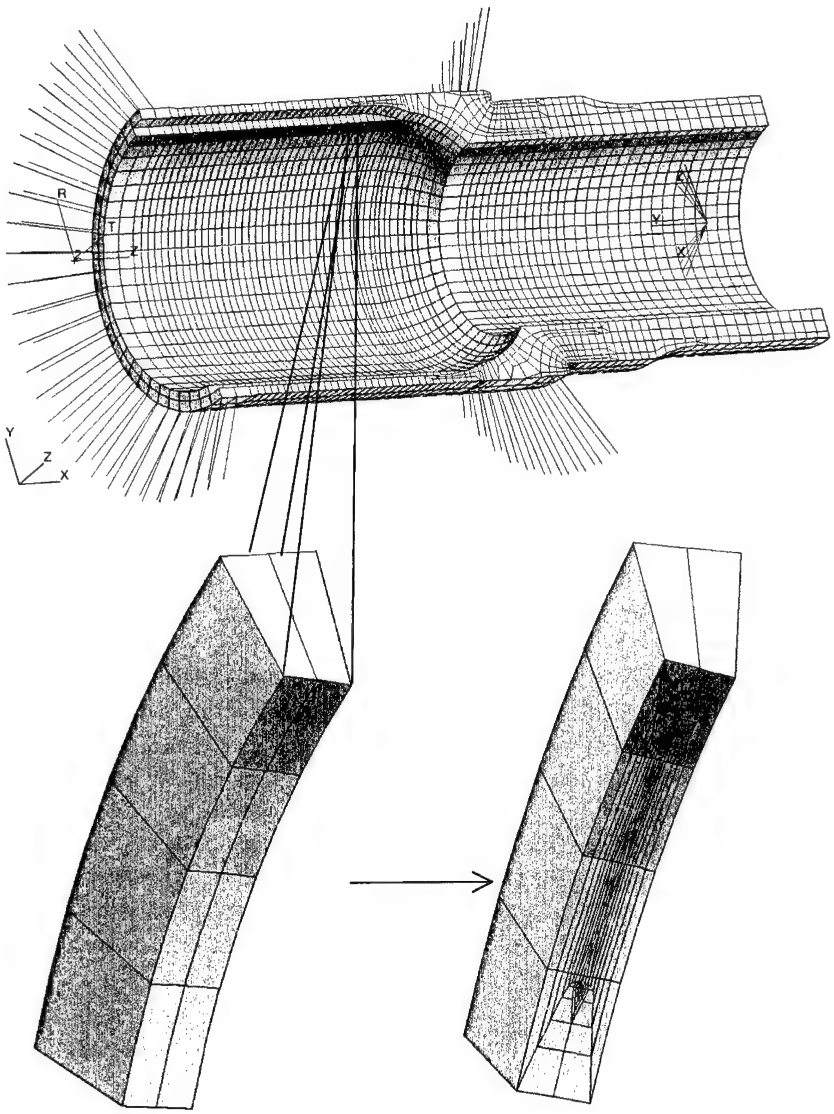


Figure 13. Modelling the crack surface: location of the crack blocks in the complete mesh

The TROS is made from 9310 steel as per specification AMS 6265. The material specification covers premium aircraft-quality, low-alloy steel. The steel is of high case

hardness (Rockwell C 60 -64) and lower core hardness (Rockwell C 30 -45). This gives the steel high strength with high fracture toughness. From the original United Technologies Sikorsky Aircraft detail drawings the hardness penetrations were found to be a maximum of 0.040 inches. Therefore, a hardness of between Rockwell C 60 and 64 is achieved at the TROS surface, to a depth of 0.040 inches, and then decreases towards the centre of the material to between Rockwell C 30 and 45. Since the hardness of the steel varies through its thickness, the mechanical properties also vary to some extent. However, any changes in modulus of elasticity due to hardness variations are relatively small. Therefore, for use as a material property in the PATRAN database, the mechanical properties were assumed to be constant.

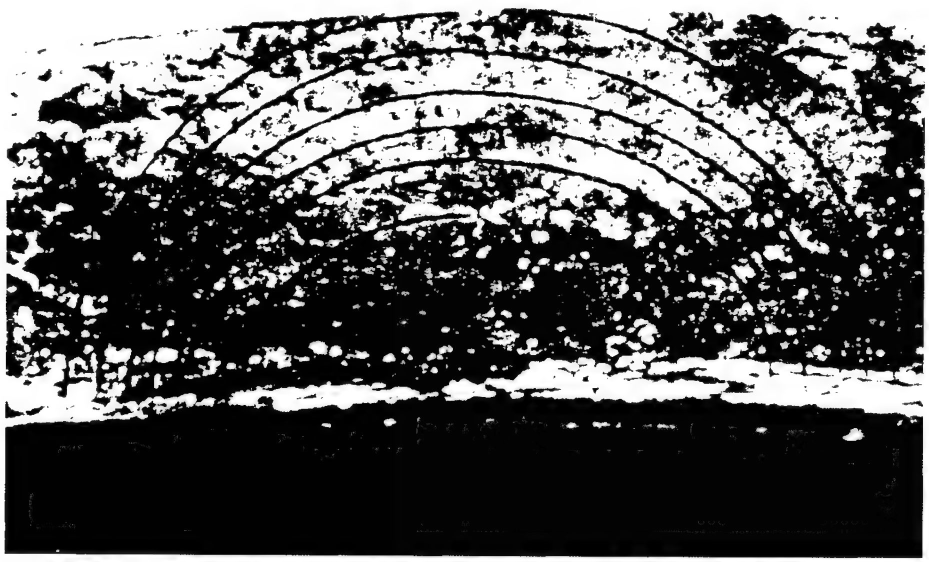


Figure 14. Possible progression markings on the fatigue fracture surface of the inboard component of the cracked TROS

Figure 14 shows the fatigue crack progression markings on the crack surface of the TROS. A plot was produced and a trend line was fitted, starting at the initial grind mark depth of 142μinches. This plot showed only the crack growth as a function of estimated fatigue life (arbitrary units) and did not accurately display the initial steps of the fatigue crack. Therefore Figure 11 can be used to compare the shape of the crack front but not the estimated fatigue life.

4.3.2 3D Crack Growth Analysis

ZENCRACK modifies the model by inserting crack blocks into specified elements within the FE model, shown in Figure 13, allowing detailed crack growth analysis to be performed. For the crack growth to be measured accurately, two ABAQUS models were required for the crack to initiate at a very small size and then to grow from the inner surface to the outer surface. Eight crack blocks were placed into each mesh as shown in Figure 13. This allowed the initial dimensions of the crack to be used and allowed ZENCRACK to continue the crack growth close to the outer surface.

The TROS sees a large number of load cycles due to the speed with which the shaft is rotating. A scale factor was used in order to convert the number of cycles that made up the ZENCRACK input, to the number of cycles per 100 hours of flight. The initial crack size could not be modelled due to ZENCRACK element sizing limitations. To get the crack to grow, the crack initiation size was 0.395 inches long and 0.012 inches deep.

The ZENCRACK analysis does not account for any Out Of Balance (OOB) that the shaft may have seen prior to its failure. Due to the computational requirements and ZENCRACK restrictions the crack could not be grown further than three-quarters of the shaft wall thickness.

4.3.3 Results and Discussions

From the progression markings in Figure 14, the crack can be said to grow predominantly in the radial direction. This was analysed by ZENCRACK and the result shown in Figure 15 shows that the primary direction of crack growth is in the radial direction, from the inner diameter to the outer diameter. The crack front shown in Figure 15 is tending towards the actual crack front geometry shown in Figure 11.

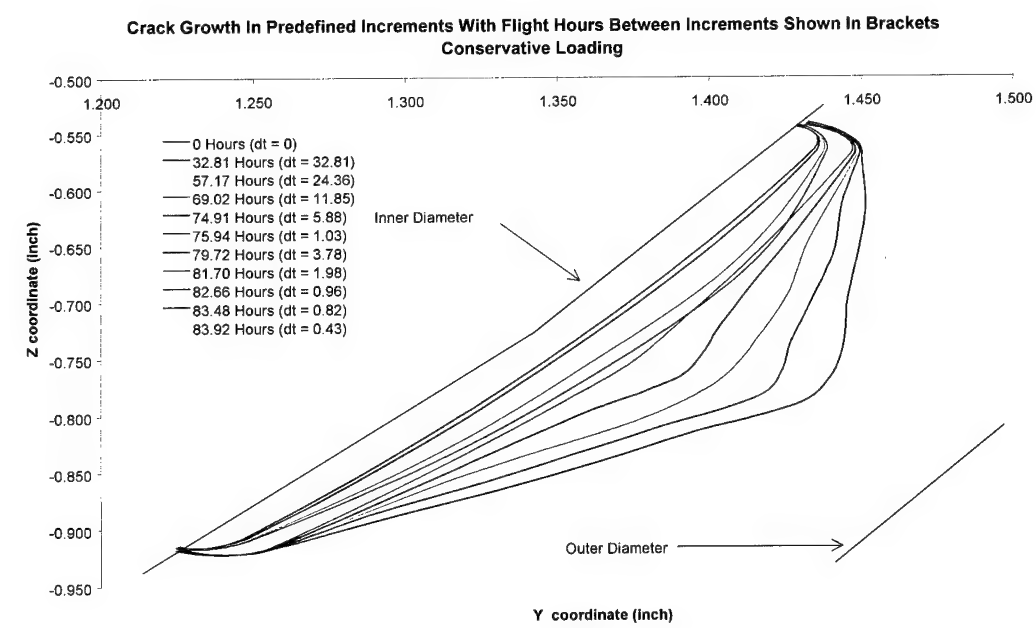


Figure 15. Crack front at pre-defined intervals from the ZENCRACK analysis.

Once the crack reaches the outer surface, the crack growth rate increases rapidly. Because of this behaviour and computational limitations the crack in the ZENCRACK model was modelled to a point where the outer surface was nearly penetrated. ZENCRACK cannot crack an element completely through by itself. The growth must

be allowed to go as far as ZENCRACK will allow (approximately 70% of element edge length depending on element shape). This is usually where a model restart analysis would be utilised. However, due to the mesh complexity and the three-dimensional crack front the model restart analysis was not allowed by ZENCRACK. This resulted in predictions being made that relate to the crack growth behaviour between the last increment of the crack growth and the next increment that requires a new FE mesh to be developed that incorporates the crack closer to the outer surface (Stages 4 to 5). Due to this complexity a decision was made that entailed modelling the crack in the TROS to a point where the crack growth reached approximately 65% of the element edge length.

As the crack in the TROS model was not going to be analysed to failure, a prediction had to be made to gain an understanding of the total life of the TROS with an existing crack. By plotting the results of the ZENCRACK analysis and fitting an exponential curve this prediction was possible. Therefore, no exact time to failure is given but an appreciation can be gained as to when the crack growth starts to be become rapid. Figure 16 shows that the growth accelerates when the crack depth reaches approximately 0.04 inches. This analysis does not account for the change in hardness of the material. ZENCRACK cannot model a varying hardness accurately because only one crack growth law can be defined for each analysis.

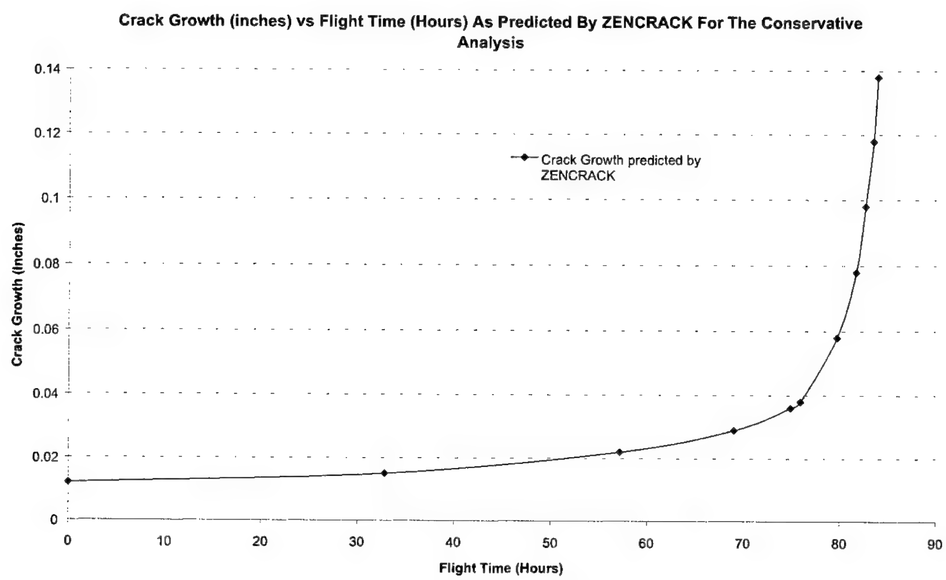


Figure 16. Crack growth rate of a 0.395 by 0.012 Inch crack In the TROS from the ZENCRACK analysis.

There are several significant limitations that ZENCRACK places on any analysis. Fatigue crack growth for a variable load spectrum is not accurately modelled due to the implementation of the characteristic K method. Crack growth outside of the region governed by the Paris equation is not modelled accurately and is extrapolated from the given data.

4.3.4 Conclusions

The ZENCRACK crack growth package was used in order to predict the time taken for a TROS FE model to fail under a standard fatigue load spectrum for a specified crack size. This involved several assumptions and limitations, some of which were as follows.

1) The crack growth model could not model the complete crack growth.
2) The crack growth model did not account for any OOB, geometry changes, heat-treatment inconsistencies or hardness variation.
3) The initial crack size could not be modelled.
4) The total time to failure was estimated using an exponential curve.

ZENCRACK with the aid of an exponential curve fitting procedure predicted that if the crack were to originate at 0.003inches depth the time to failure would be approximately 100 to 150 hours. The US Army EH-60 Black Hawk lost its tail rotor drive at 580 hours and the Chinese Black Hawk at 350 hours. The U.S. Army Black Hawk TROS has a CRT of 5100 hours.

4.4 3D Crack Growth Analysis for TF30 3rd Stage Fan Disc

4.4.1 Background

The discovery of a crack in a second stage fan disc during a routine inspection of a TF30 engine in Sept 1999 resulted in the temporary grounding of the RAAF's entire F-111 fleet pending further information. Subsequent inspections revealed multiple cracks in the bore region of a bolthole of a third stage disc. An immediate requirement arose to determine their likely implications for the disc life as well as to assess the possible risk in continued fleet operation, requiring studies of crack growth rate and critical crack length.

4.4.2 Problem Definition

The objective of this particular study was to determine the crack growth rate for a crack emanating from the centre of bore of a bolthole and to estimate the critical crack length. The major concern was the crack in the radial direction, initiating at the inner bore of the bolthole and growing towards the disc bore. Figure 17 illustrates the geometry of the 3rd stage fan disc and the crack growth direction.

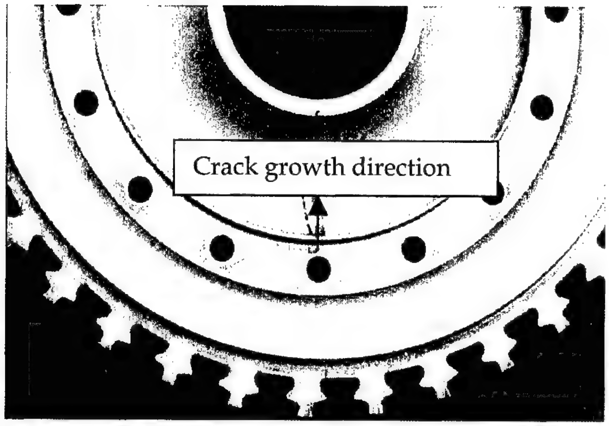


Figure 17. Disc geometry and crack growth direction

As the 3rd stage disc is connected to adjacent components, a 3D assembly FE model of 22.5° segment was created to determine the global behaviour. The assembly model includes 3 fan discs, adjacent spacers and air seals made of the material Ti8-1-1. All components were meshed using 20 noded brick elements and a uniform coarse mesh was used throughout the model. The 3D FE assembly model is show in Figure 18.

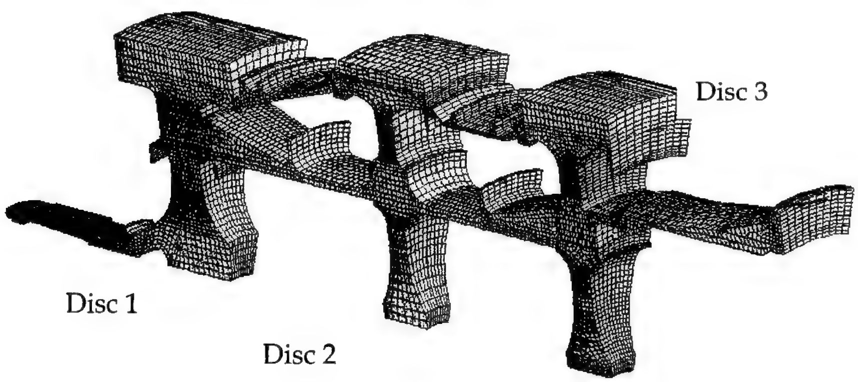


Figure 18. 3D FE model of the disc assembly.

It is worth noting that the local features of discs, such as bolt holes and the flange rivet holes and cut-out, were not included in the assembly model, as the major concern here was to determine the behaviour of the assembly under normal operating conditions. The applied loads include the centrifugal load, the thermal load and inertia load of blades under military power setting [20]. Appropriate boundary conditions were applied to the 1st stage disc and the spacer between the 3rd and 4th discs to represent the bearing support and the constraint from the 4th disc respectively. The stress analysis was performed using ABAQUS software and displacement solutions were obtained for the detailed analysis of the 3rd stage disc.

Once the global behaviour of the disc assembly was obtained a detailed 3D FE sub-model of a 22.5° segment was created for the 3rd stage disc including all the local geometry features as shown in Figure 19.

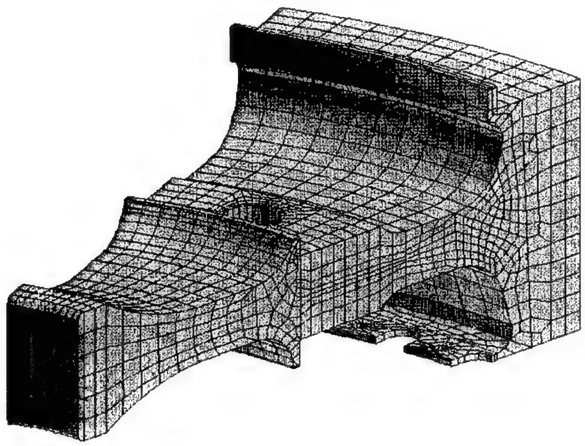


Figure 19. 3D FE model of the 3rd stage Disc.

The solutions from the 3D FE assembly model were then applied to the cutting boundaries in the submodel using a sub-modelling technique [14]. The centrifugal load, thermal load and the inertia load of the blades [20,25] were applied to the submodel, and the stress fields at the bolthole region were then determined, shown in Figure 20.

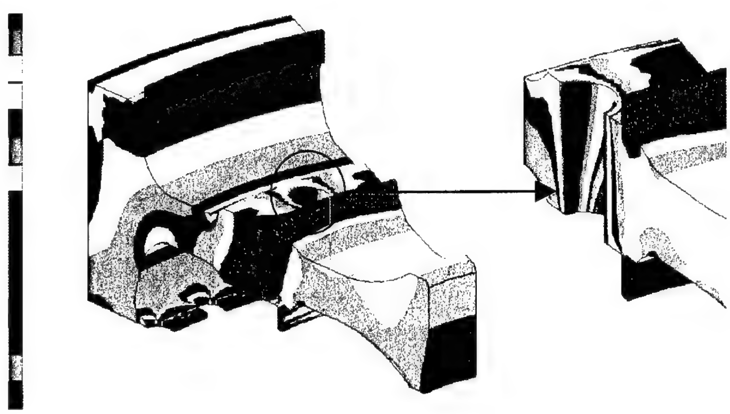


Figure 20. Maximum principle stress distribution for the 3rd stage disc.

As shown in Figure 20 the stress at the inner bore of the bolthole is about 435 MPa. The stress distribution indicates that a crack at the inner bore is likely to grow in the radial direction.

4.4.3 3D Crack Growth Analysis

In the submodel of the 3rd stage disc, 4 crack blocks required by ZENCRACK were defined and block sizes were chosen such that the mesh at the crack region would not be distorted. An initial radial crack with a semi-circular shape (0.2mm in radius) was inserted in the bore of the bolthole on the inner side using ZENCRACK. This was implemented by replacing the pre-defined crack blocks with crack elements embodying cracks having specified size, shape and orientation. Figure 21 shows the mesh modification by ZENCRACK for a detailed crack growth analysis.

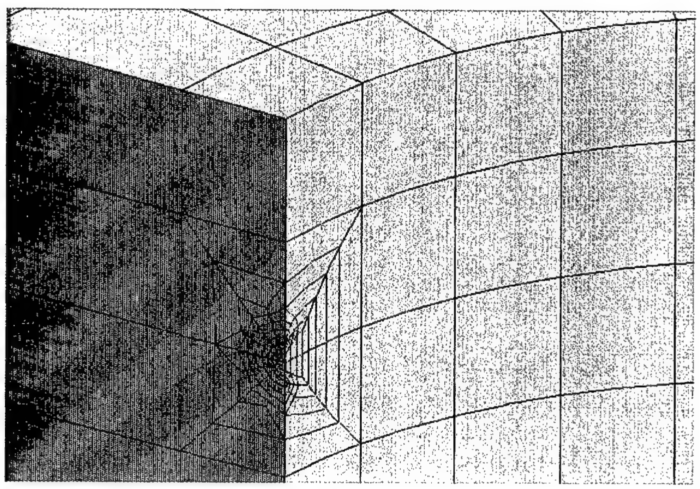


Figure 21. FE model with crack blocks (0.2mm by 0.2 mm configuration)

It should be noted that the final crack size is limited by the size of the crack block. The crack block has to be small enough to ensure the quality of mesh after a small initial crack is inserted but large enough to provide for sufficient crack growth. Once the crack size reaches to 80 percent of the crack block size ZENCRACK terminates the crack growth. Therefore a new FE submodel with large crack block size had to be created using input from the previous model to restart the analysis for further crack growth. Overall, three submodels were created including the original FE submodel and two new models to overcome the limitation of the crack block size.

The stress intensity factor was calculated prior to conducting crack growth calculations to ensure that stress intensity factors along the crack front would be above threshold and therefore support crack growth. Figure 22 shows the calculated stress intensity factors for three crack configurations, expressed in terms of the half crack length by the crack depth.

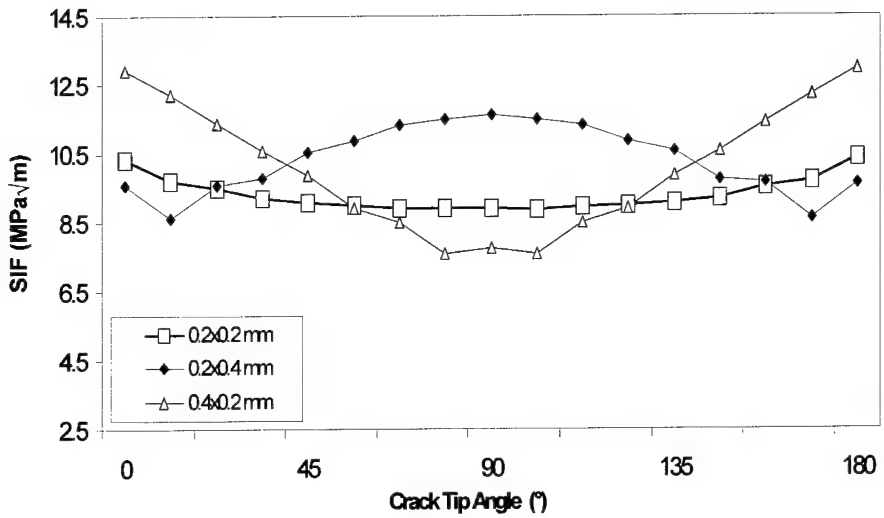


Figure 22. Stress intensity factor for 3 different crack configuration

In the absence of a detailed RAAF loading spectrum, a simplified but representative spectrum was used [18]. A scaling factor was used in order to convert the number of cycles used in ZENCRACK to the number of cycles per 1000 hours of engine flight. Crack growth data for the material Ti-8-1-1 was obtained from the published literature [22,23] and interpolated to the same temperature at the bolthole region. The stress intensity factor is above the threshold of the material Ti8-1-1 (between 2 Mpa $\sqrt{m}$ and 8 Mpa $\sqrt{m}$) and hence clearly the crack will propagate.

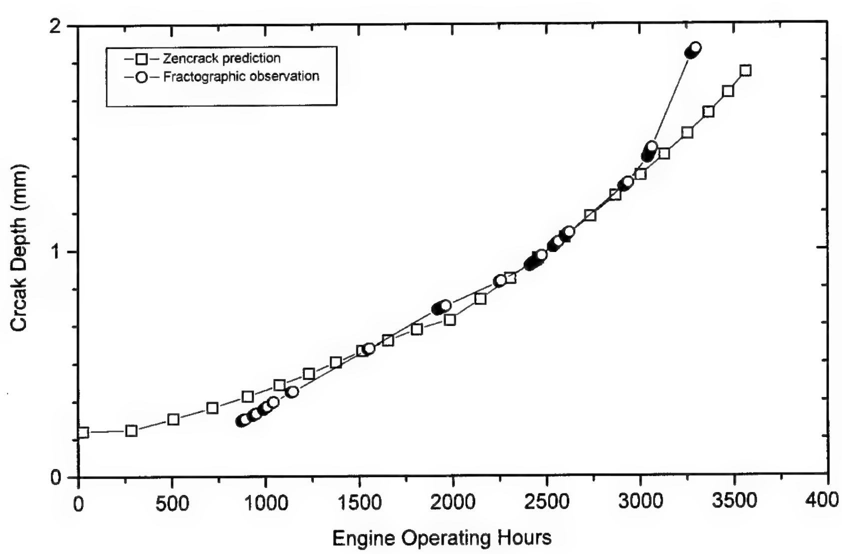


Figure 23. Predicted crack growth rate compared with the one from fractographic observations

An initial crack 0.2 mm deep by 0.4 mm wide was inserted in the centre of the bolthole bore for crack growth analysis. Figure 23 shows the crack growth curve from the ZENCRACK analysis and its comparison with the fractographic observation [24]. The results correlate well but it is worth noting that a considerable difference exists at the ends of the two curves. This is due to the fact that the Paris law is used and it is limited to only the stage II crack growth. For a better prediction at the two ends a more sophisticated growth law may have to be considered and implemented.

4.4.4 Discussion

The ZENCRACK code can be readily used to insert a crack into a general 3D component and the stress intensity factors can be calculated using ABAQUS under arbitrary loading conditions including both mechanical and thermal loading. This is a highly desirable feature for the calculation of stress intensity factors for components with complicated geometries because analytical solutions may not exist for various crack configurations in those components.

However, there is a limitation in that crack growth rate can be only expressed in the form of a basic power law [26]. The crack growth law implemented in ZENCRACK applies only to linear elastic fracture problems and therefore any retardation induced by local plasticity along a crack front is excluded. Fatigue crack closure may have a significant effect on fatigue crack growth rate [27,28] and this cannot be included in the ZENCRACK model. For more accurate crack growth modelling, the plasticity induced crack closure must be taken into account [28].

There are additional limitations on crack shape transitions and crack block divisions during crack growth analysis in ZENCRACK. The transitioning process from a surface crack to a through crack cannot be modelled due to excessive distortion of the elements. As a result, the crack growth has to terminate before the crack becomes a through crack. The element division for each crack block cannot be changed during a crack growth analysis and the mesh pattern has to be kept constant for a crack block throughout the analysis. This may impose numerical errors into the crack growth results since the initial mesh density may be sufficient for the solution precision of the initial crack size but may produce numerical errors for the solution of a large crack during progressive crack growth.

Crack growth analysis under spectrum loading cannot be accurately modelled using ZENCRACK. The characteristic K method used in ZENCRACK assumes that the amplitude of each load is weighted by the rate of cycle occurrences. Consequently only an equivalent constant load is used to calculate the stress intensity factor for crack growth. Therefore a load spectrum has been represented by a single load, and the effects from load sequence and possible over-loads are all excluded.

4.4.5 Conclusions

A numerical crack growth prediction method implemented in ZENCRACK together with finite element analysis has been used successfully to predict a three dimensional surface crack growth in the TF30 3rd stage fan disc under both centrifugal and thermal loading (military operation loading condition). The stress intensity factors along the 3D crack front were readily determined using the ZENCRACK and the crack growth rate was predicted.

The predicted crack growth rates correlate well with fractographic observations in the middle range but there are noticeable deficiencies at the two ends. It is believed that these differences are caused by the simplicity of the crack growth law implemented in the ZENCRACK. For accurate prediction, some critical factors have to be addressed and incorporated. The fatigue crack closure has a significant effect on fatigue crack growth rate and it should be included in the crack growth modelling so that the plasticity-induced closure can be modelled. This is important when the crack growth retardation and acceleration need to be considered under spectrum loading. The simplification of spectrum loading in ZENCRACK is a deficiency that may have a significant impact of the precision of the crack growth prediction for a component under complicated loading spectrum.

It must be pointed out that the linear fracture mechanics is the basic foundation in ZENCRACK for crack growth modelling. Therefore the deficiencies in the crack growth prediction can be related to the limitation of the method adopted.

5. Conclusions and Recommendations

A critical review of ZENCRACK capabilities has been completed by examining the basic methodologies implemented and by excising the program in four practical applications. The following general conclusions can be drawn:

1. ZENCRACK is most useful for inserting cracks with complicated shapes into existing 3D FE meshes. The feature of the crack block mesh significantly reduces meshing time and modelling complexity. In addition the compatibility with analysis software such as ABAQUS is a positive feature, allowing the stress intensity factors to be readily calculated for complex geometries and crack shapes.

2. Both mechanical and thermal loads can be included in the calculation of stress intensity factor and crack growth, although this is more related to the capability of the ABAQUS finite element packages that ZENCARCK interfaces with. The sub-modelling can be used together with ZENCRACK as well.

3. The crack growth modelling is based on the principle of linear elastic fracture mechanics and is therefore limited to crack growth analysis in linear elastic

domains. The crack growth law (Paris equation) implemented in ZENCRACK is too basic for the accurate prediction of crack growth in many practical situations.

4. For spectrum loading conditions, ZENCRACK adopts the characteristic K method that compounds all loading conditions into an equivalent constant amplitude sequence. This simplification may result in inaccuracies in prediction of crack growth under complex loading.

5. Any effects induced by local plasticity, such as closure and retardation, cannot be included in the crack growth predictions and this may have significant effect on the accuracy of predictions.

6. The transitioning process from a surface crack/corner crack to a through crack cannot be modelled using ZENCRACK due to the fact that FE meshes do not cope with the sudden changes in the level of geometry topology.

7. The mesh pattern has to be constant for a particular crack block throughout an analysis. The solution precision may be sufficient for the initial crack size if a proper element division is chosen but can be sacrificed with the progressive increase of crack length.

8. For continuous crack growth, the crack blocks have to be changed manually and remeshed several times in order to accommodate the crack size increase for each restart analysis.

In summary:

1. ZENCRACK is a useful tool for the calculation of stress intensity factors for cracks inserted into 3-D components under arbitrary loadings.

2. The crack growth law implemented in ZENCRACK is quite basic. For more accurate prediction, advanced crack growth models need to be implemented and utilised together with 3D numerical analysis techniques.

6. Acknowledgments

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19. ABSTRACT

DSTO has been continuously enhancing its capability to provide through-life support to the ADF in aircraft engine life extension and engine component life management. One of the major requirements is an enhancement in computational 3D crack growth modelling and analysis. This report presents the critical issues involved in 3D crack growth and evaluates the results of a 3D crack growth capability in the ZENCRACK software with an emphasis on its validity and applicability to our major requirements. The primary issues to be dealt with in practice for 3D crack modelling are outlined together with the limitations of existing software. The methodology and techniques implemented in ZENCRACK are described and discussed. Four practical applications of ZENCRACK and individual evaluations for particular problems are presented and discussed in detail. The various limitations and uncertainties encountered in the practical applications are identified. In particular, it is found that ZENCRACK is a useful tool for the calculation of stress intensity factors but is limited in terms of its accuracy for predicting crack growth rate. Conclusions and recommendations are made for more accurate 3D crack growth modelling.

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